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An experimental investigation concerning the effect of concave surface curvature on a radial wall jet

Stanley E. Pace
Lehigh University

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in Candidacy for the Degree of

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in

Mechanical Engineering

and

Engineering Mechanics

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AN EXPERIMENTAL INVESTIGATION CONCERNING THE EFFECT OF CONCAVE SURFACE CURVATURE ON A RADIAL WALL JET

by

Stanley Eugene Pace

A THESIS

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(date)

Benjamin E. Nevis
Professor in Charge

Ferdinand P. Beer
Head of the Department

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ABSTRACT

The radial wall jet is a type of flow which occurs when an initially circular jet of fluid impinges on and spreads out over a surface symmetrically with respect to an axis perpendicular to the surface, located at the point of impingement. The medium surrounding the surface is of the same phase as the jet fluid. This type of jet flow is used to produce films for the heating, cooling and drying of surfaces.

This thesis pertains to an experimental investigation of the effect on a turbulent radial wall jet when the surface on which the jet impinges is a concave surface of revolution. The surfaces used were three hemispherical shells of radii 6, 9, and 12 inches. The results from the hemispherical shells were compared to the results obtained when the surface of impingement was planar. The aspects of the wall jet considered were the growth of the boundary layer thickness, the decay of the maximum velocity and the shape of the dimensionless velocity profile.

It was found that the boundary layer thickness increased as the radial distance from the origin to the 0.78 power for the hemispheres and to the 1.18 power

for the plane surface. The maximum velocity was found to decrease as the radial distance to the -0.89 power for the hemispheres as compared to the -1.04 power for the plane surface. Two adjustments for curvature were tried in attempts to obtain a better method of correlating the data from the concave surfaces. The dimensionless plots of the velocity profiles revealed no difference between those from plane surface and those from the hemispherical surfaces. The conclusions drawn were that the concave surface tended to decrease the rate at which the boundary layer grew and decrease the rate at which the maximum velocity decayed. Also for surfaces with radii of curvature greater than 9 inches the effect of curvature could be considered negligible.

Introduction

The wall jet, sometimes referred to as a submerged jet, is a type of flow where a jet of fluid impinges on and spreads out over a surface which is submerged in a medium of the same phase as that of the jet fluid. The jet may be initially planar or circular; it may impinge at any angle of incidence ranging from tangential to normal to the surface and the surrounding medium may be initially stagnant or moving. The term radial wall jet applies when a circular jet of fluid spreads out over the surface symmetrically with respect to an axis perpendicular to the surface, located at the point of impingement; this type of wall jet is shown diagramically in Figure 1.

The wall jet has been used in practical applications to produce films for heating, cooling and drying of surfaces. The application of a radial wall jet to the fuel pressurization system of liquid propellent rockets has led to an interest in the effect on the wall jet of a curvature in the surface on which the jet impinges. This interest resulted in the experimental investigation described in the following thesis.

The analytic problem of a radial wall jet was first

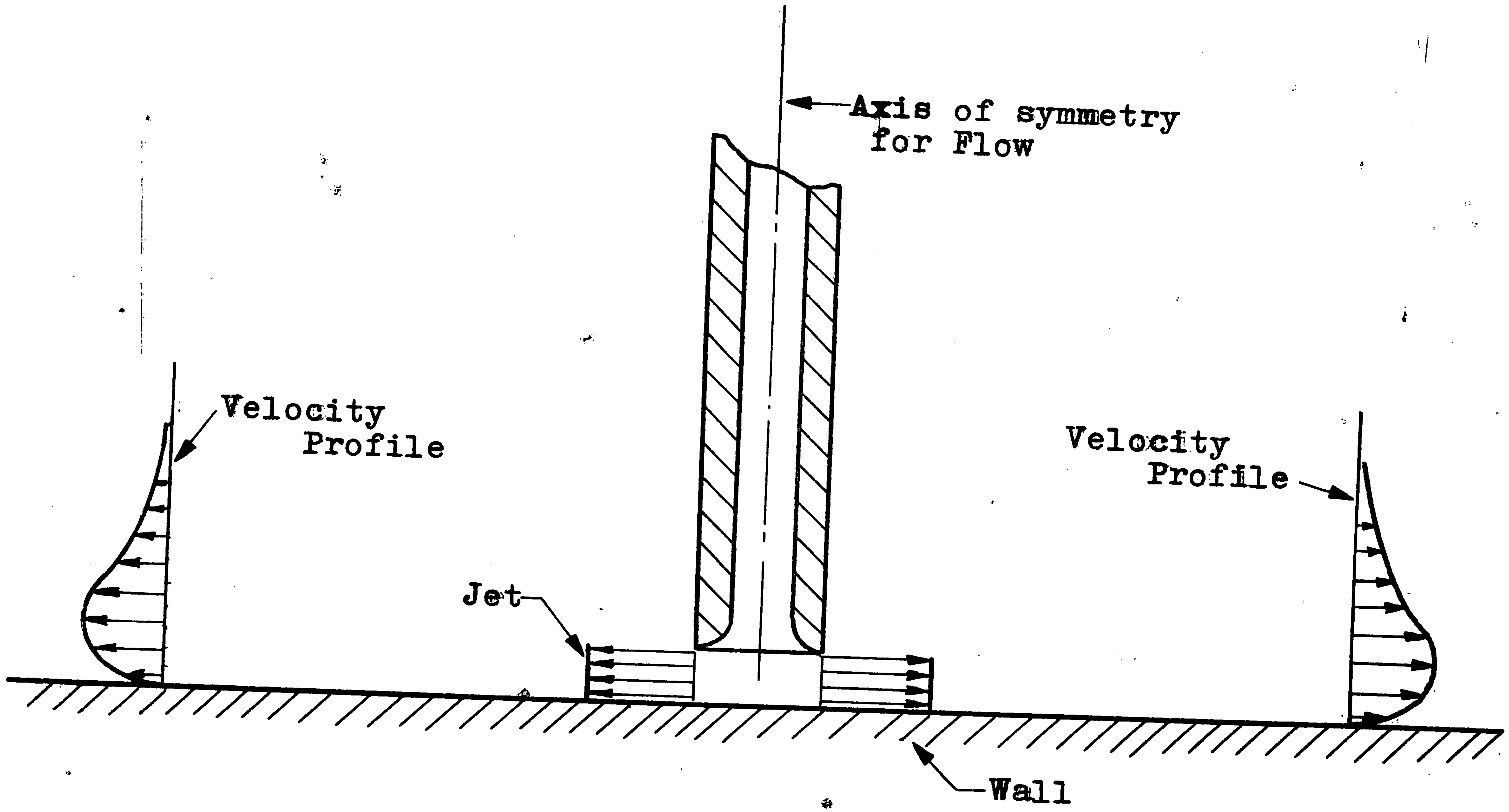


Figure 1. Schematic of Radial Wall Jet

treated by M. Glauert (1)[1]; he developed solutions to the governing equations for both the laminar and turbulent radial wall jet on a plane surface when the surrounding medium was stagnant. The problem was first studied experimentally by P. Bakke (2) and then analytically and experimentally by Poreh, Tsuei and Cermak (3). No work to date is known to have been done for the case of a turbulent radial wall jet on a curved surface.

The objective of the experimental investigation conducted was to measure the velocity profiles of the boundary layer formed when a turbulent radial wall jet impinges on a concave surface of revolution and a plane surface and from these velocity profiles to determine the effect of surface curvature on the growth of the boundary layer, the decay of the maximum velocity and the shape of the velocity profile. The concave surfaces tested were three hemispherical shells of radii 6, 9, and 12 inches. A hot wire anemometer and boundary layer probe were used to measure the mean velocity profiles.

[1]Numbers in the brackets designate References listed at the end of the thesis.

Apparatus

A schematic of the experimental set-up used to obtain data for the case of a radial wall jet on a flat surface is shown in Figure 2. The reason for producing the wall jet as shown was that this was the method to be used in the investigation of surface curvature effects and it was desirable to keep the initial conditions the same. The flat surface was an aluminum plate 10 inches by 18 inches and 1/8 of an inch thick, hand sanded with coarse emery paper. The plate was electrically insulated by means of the plastic ring shown in Figure 2; this prevented a short circuit between the plate and the probe of the hot wire anemometer when the probe was brought proximate to the plate. The fluid used for the wall jet was dry air. A reciprocating compressor was used to supply air to a large plenum tank after which the air was dried and fed into another plenum tank which served as the source of air for the experiment. The system pressure was maintained between 60 and 70 psig. and the experiment was conducted in an environment maintained at 70 degrees fahrenheit by an air conditioning system.

The velocity measurements were made with a constant

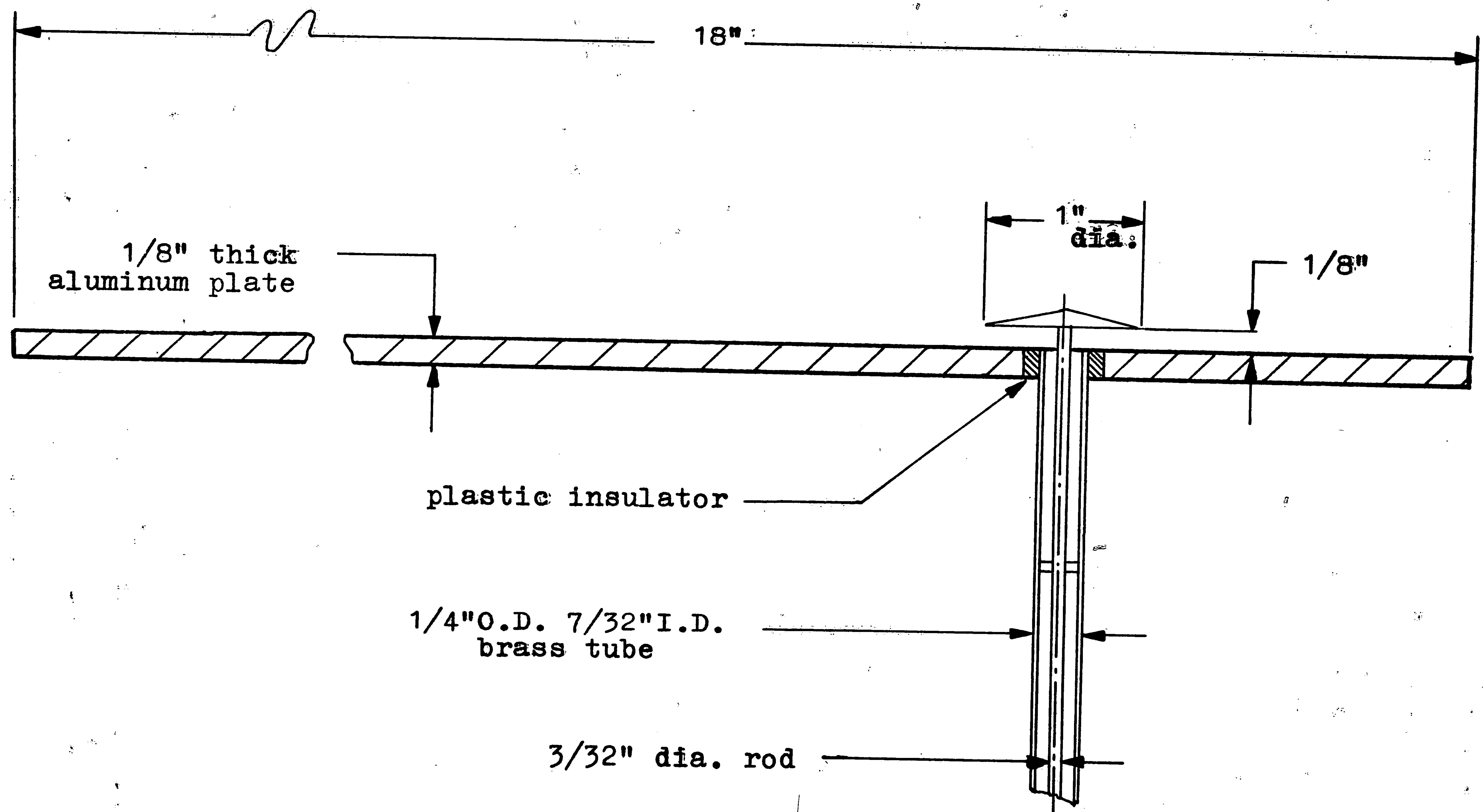


Figure 2. Experimental Arrangement for the Radial Wall Jet on a Flat Surface

temperature hot wire anemometer model 700 manufactured by Flow Corporation. A boundary layer probe, type P-4-C, with a single sensing element was used. The sensing element was a 0.00035 of an inch diameter tungsten wire 0.04 of an inch long. The output of the hot wire anemometer was monitored on a voltmeter; the voltage read was linearly proportional to the velocity. The probe was calibrated in a calibration tunnel; the proportionality constant used was the average of the constants determined at four velocities.

The probe was held in a jig where the vertical position was controlled by a micrometer head having a smallest marked division of 0.0001 of an inch. The total allowable travel was one inch. For each vertical traverse the probe was brought down to contact the plate and the vertical positions were referenced from this reading which was taken to be at a distance of 0.080 of an inch from the surface, half the diameter of the tip of the probe. The point of contact could be estimated within 0.005 of an inch. The radial distance from the origin was measured with a scale having a smallest division of 1/32 of an inch.

A schematic representation of the experimental apparatus used in the investigation of the effect of surface curvature on a radial wall jet is shown in Figure 3.

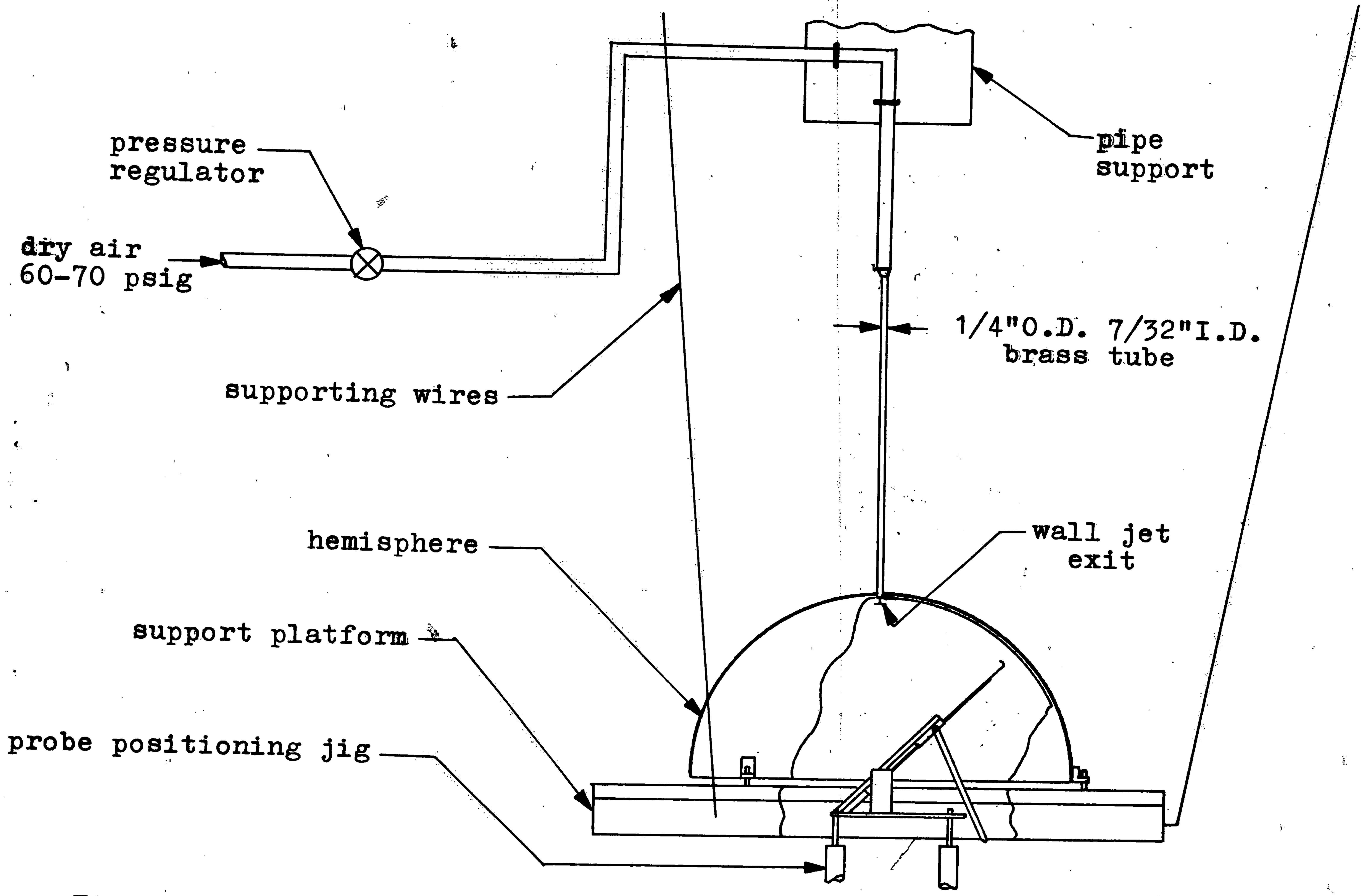


Figure 3. Experimental Arrangement for the Radial Wall Jet on a Concave Surface

Three different diameter hemispheres were used as the concave surfaces giving nominal radii of curvature of 6, 9, and 12 inches. The hemispheres were spun from aluminum to these radii within a tolerance of $\pm$ 1/32 of an inch; the hemispheres were hand sanded with coarse emery paper to give the same surface finish as that of the aluminum plate. The radii of each hemisphere was checked with a dial indicator and found to be within the tolerance specified.

The platform used to support the hemisphere was hung from the ceiling by three wires and steadied by three lateral supports to nearby walls. The platform was situated so that it would be approximately 4 feet above the floor and 3 feet from any wall. The hemisphere was placed with the concave surface facing down over a hole cut in the platform one inch larger in diameter than the internal diameter of the hemisphere. The hemisphere itself was supported by leveling screws in three blocks attached to the exterior surface. The wall jet was introduced into the top of the hemisphere as shown in Figure 4.

The velocity measurements were again made with a hot wire anemometer and a boundary layer probe. The position of the probe inside the hemisphere is shown schematically in Figure 5. The design considerations for

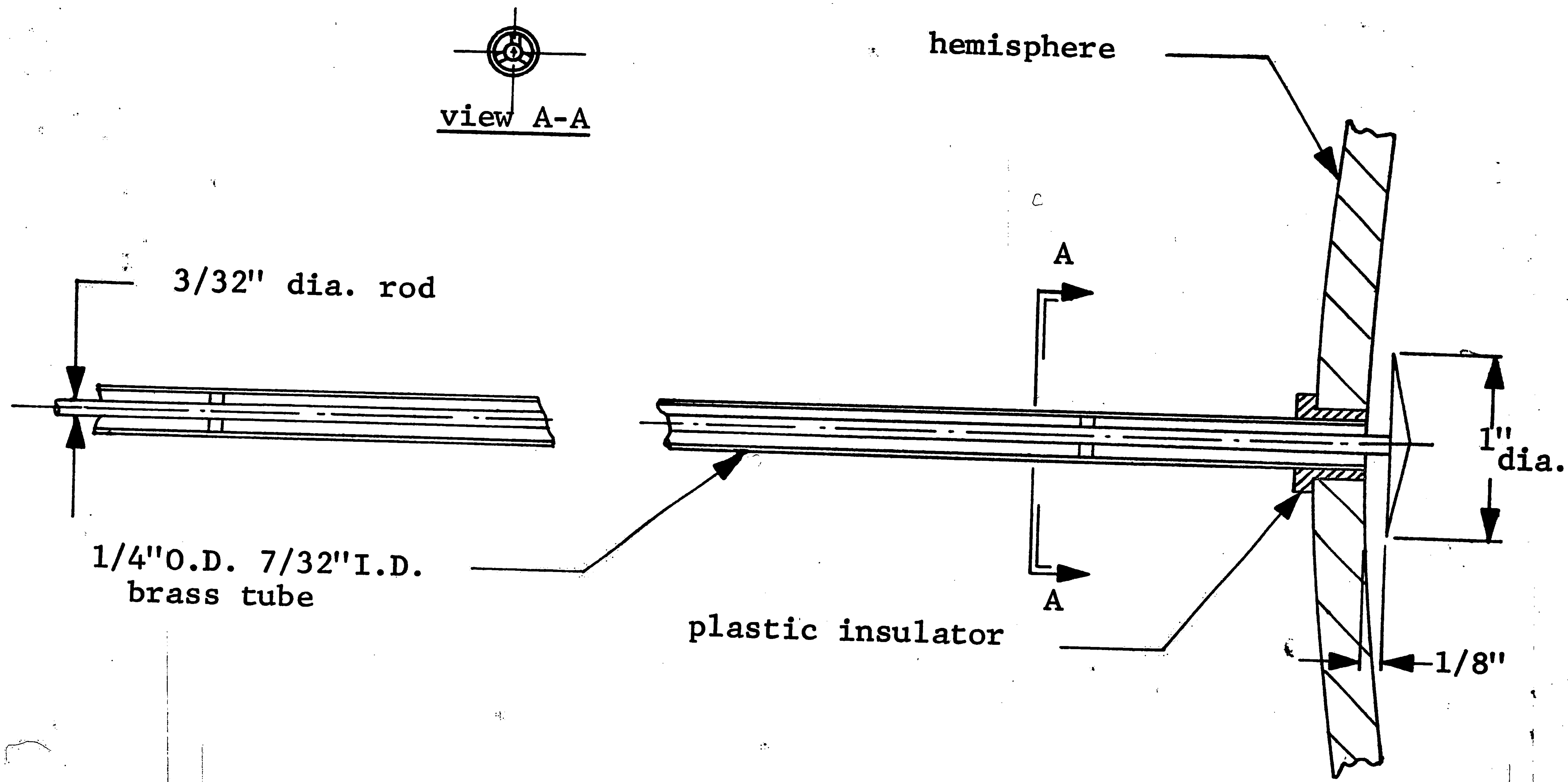


Figure 4. Method of Producing the Radial Wall Jet in the Hemispheres

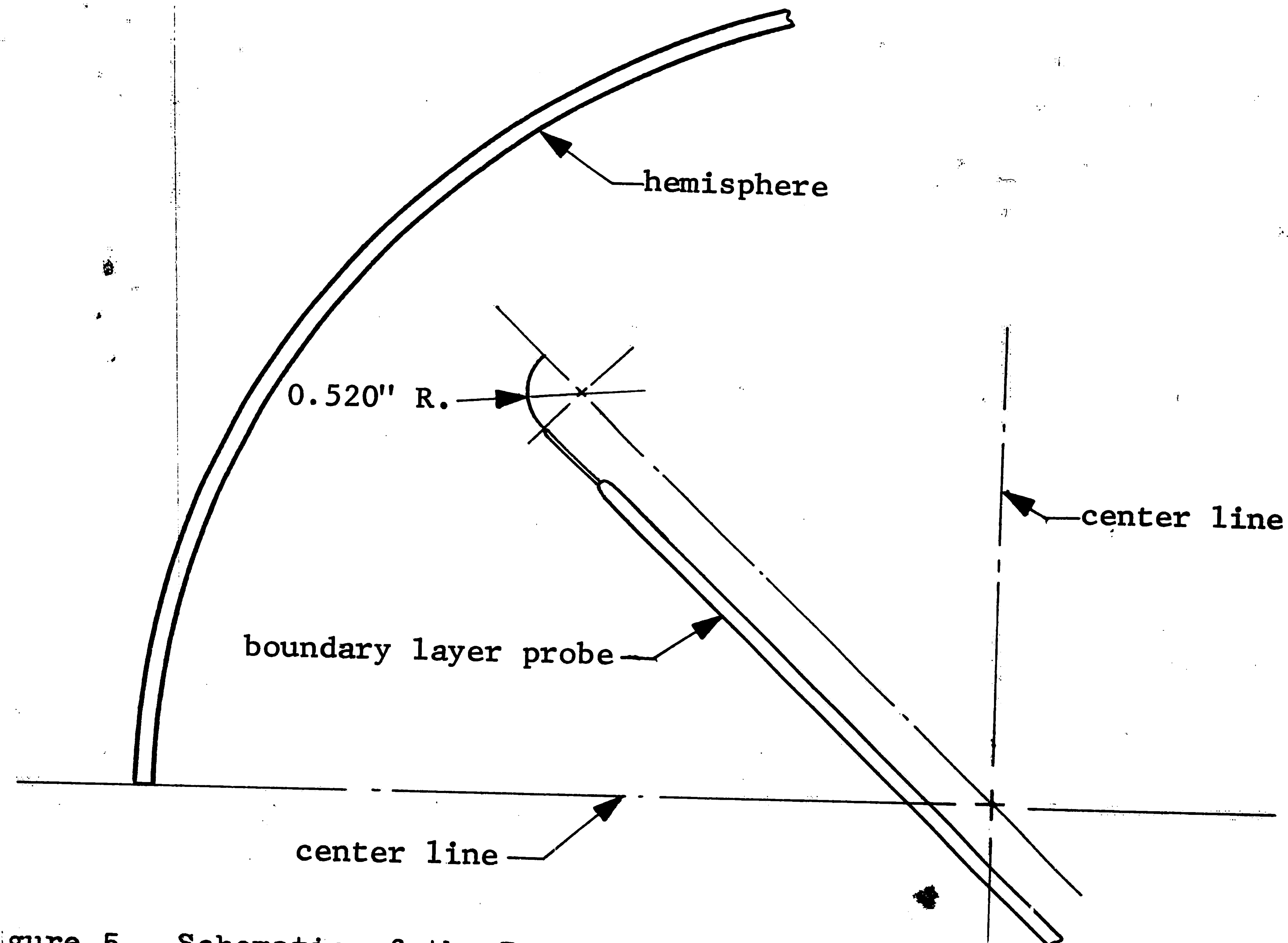
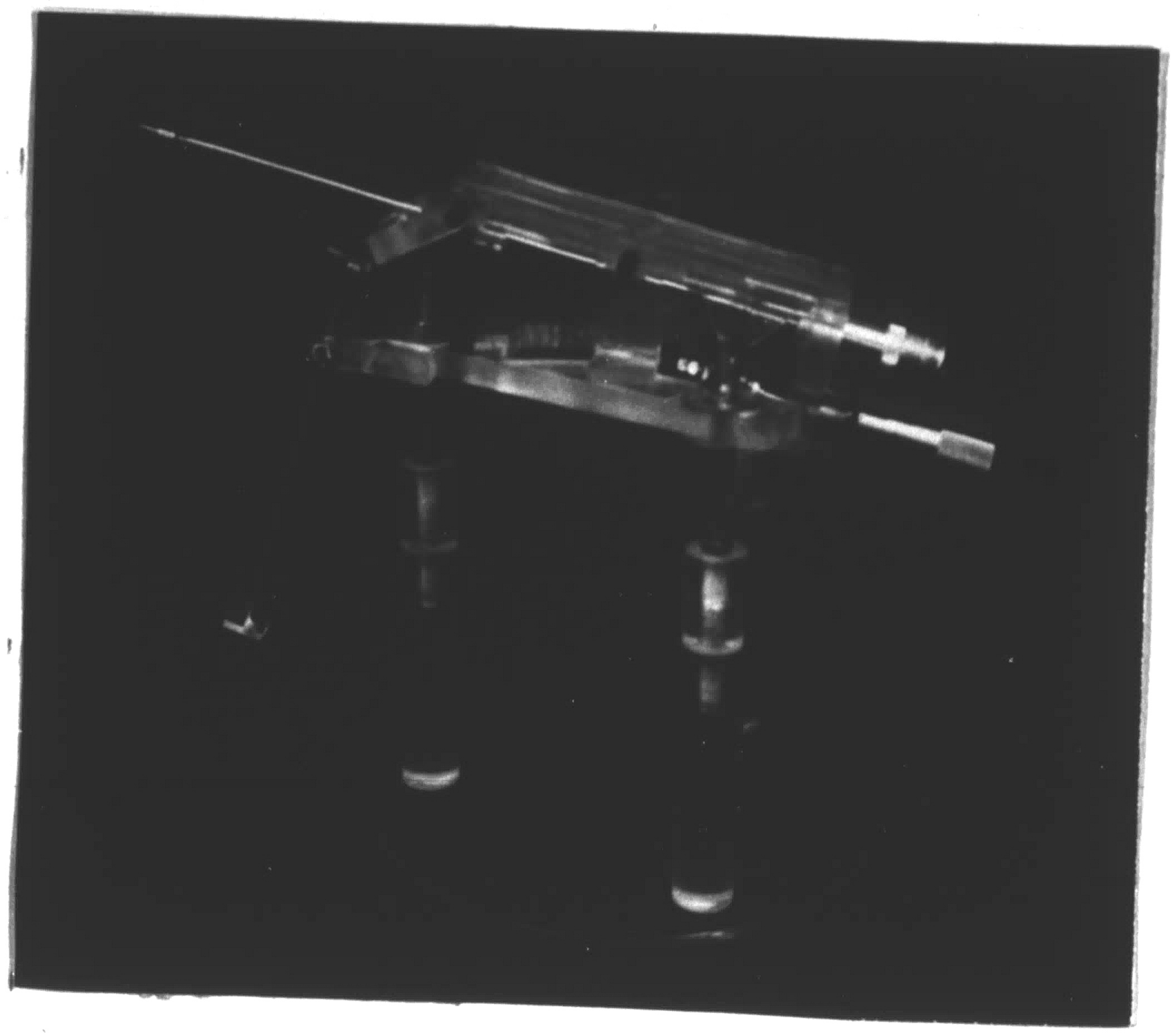


Figure 5. Schematic of the Position of the Boundary Layer Probe with respect to the Hemisphere

the probe holding jig were that the probe must move perpendicular to the wall, i.e. along a radius, and the position of the probe with respect to the wall must be known within 0.005 of an inch. Also, the azimuth angle and the cone angle had to be variable. A photograph of the resulting jig is shown in Figure 6-A; it is shown in position in the hemisphere in Figure 6-B. The position along a radius was determined with a micrometer having a smallest division of 0.001 of an inch and the cone angle was determined with a protractor mounted on the jig having a smallest division of a half of a degree.

The correct positioning of the jig with respect to the hemisphere was important. By inserting a rod having the basic dimensions of the boundary layer probe into the probe carriage of the jig and allowing the tip of the rod to ride along the inside surface of the hemisphere at an angle slightly above the horizontal the proper vertical centerline could be established. Then by lowering the carriage to a horizontal position and knowing whether the spun shell represented a complete hemisphere the plane in which the horizontal centerline lay could be found. It was estimated that the center could be located within 1/32 of an inch in either plane.



(A)

(B)

Figure 6. Probe Holding Jig

Testing

The testing of the hemispheres consisted of measuring the mean velocity profiles at five different angular positions on each hemisphere at three different exit velocities. Approximately twenty velocity readings were taken for each traverse; the probe was moved up until it contacted the surface and this was taken to be the first reading. From this position the probe was moved at 0.010 of an inch intervals until the point of maximum velocity was passed and then the intervals were increased to 0.020 or 0.050 of an inch depending upon the velocity gradient perpendicular to the wall. Checks for symmetry were made on the hemispheres and the flat plate; velocity profiles were compared at a given radial distance from the exit on 120 degree increments around the exit. A plot of one such check is shown in Figure 14. For the purpose of making a comparison between the hemispheres and the flat surface the velocity profiles were matched 1.00 inch from the exit where the velocity gradient in the direction of flow would not be very steep. The velocity profiles were matched on the 12 and 18 inch diameter hemispheres and the flat plate; these profiles are shown in Figure 15-A. Traverses were taken at positions corresponding to the same radial distances from the exit; five different radial positions were checked. Two additional velocities were then run on the flat plate and traverses were taken at radial positions approximating those measured on the hemispheres.

Results

The aspects of the wall jet to be considered are the growth of the boundary layer, the decay of the maximum velocity and the shape of the velocity profile. The boundary layer thickness is defined as the distance from the surface where the velocity of the flow decreases to half the maximum velocity, shown schematically in Figure 7.

In Figure 8 the boundary layer thickness, δ , is plotted versus the radial distance from the origin, R, on logarithmic coordinates for the flat surface. The distance R is the length measured from the center of the 1.0 inch diameter button shown in Figure 2 to the location of the probe tip. The solid line drawn through data was obtained from a least squares curve fit where the natural logarithm of the boundary layer thickness was the dependent variable and the natural logarithm of the radial distance was the independent variable. The resulting equation is of the form:

$$\log_e \delta = A + m(\log_e R)$$

or

$$\delta \propto R^m$$

The exponent m is 1.18. The broken lines on each side

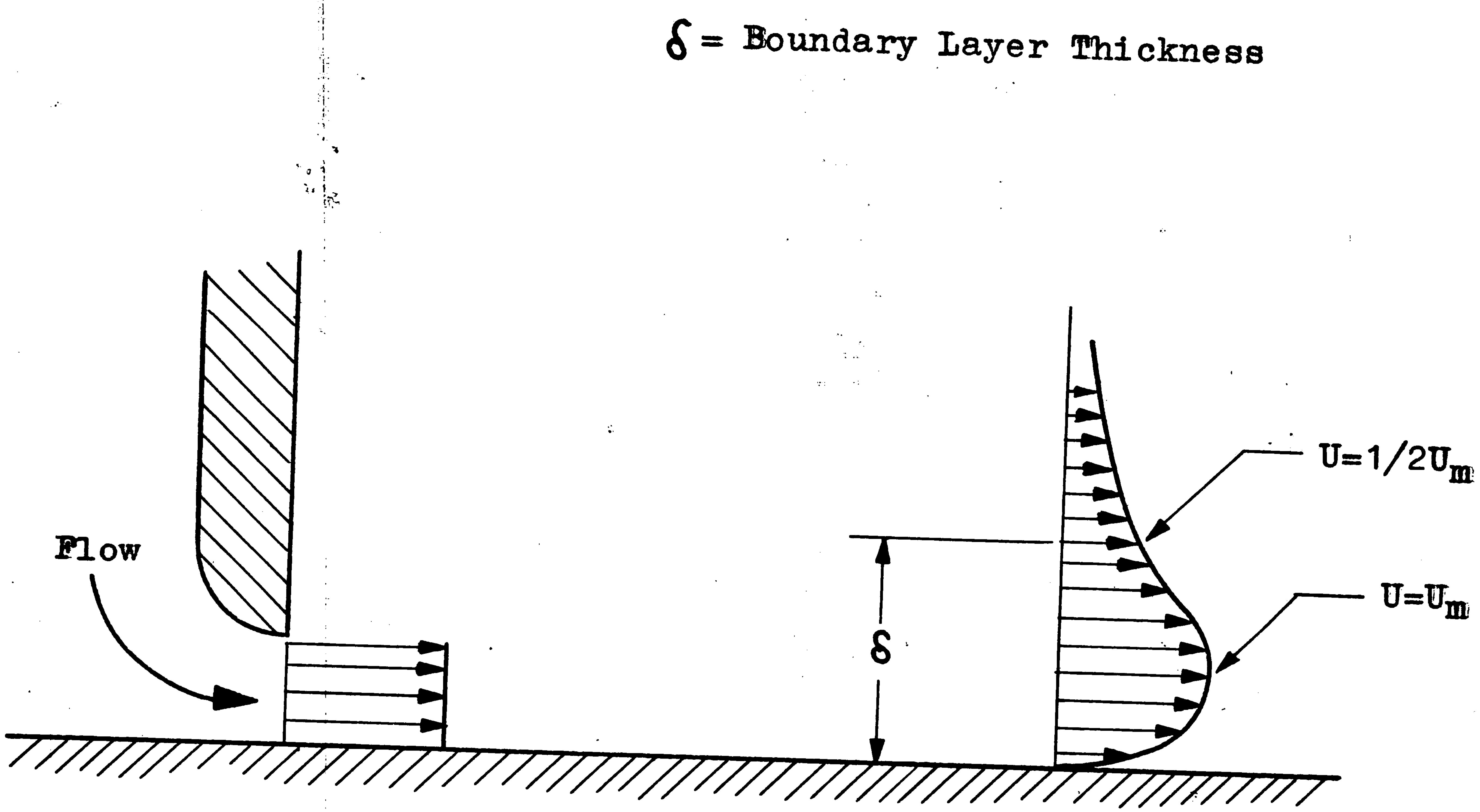


Figure 7. Schematic Description of the Boundary Layer Thickness

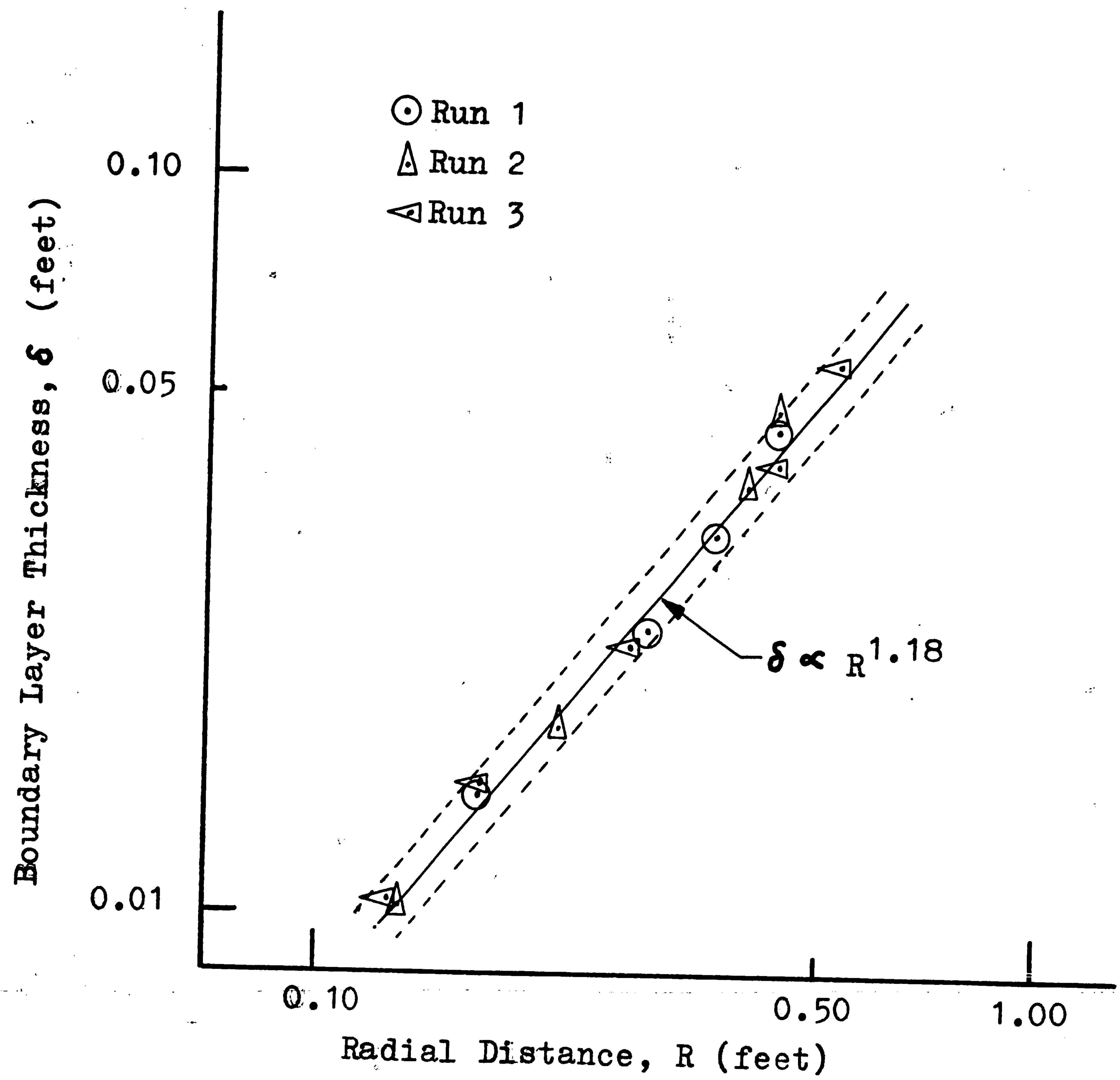


Figure 8. Boundary Layer Growth on the Flat Surface

of the solid line represent the 95% confidence band based on the standard error.

The decay of the maximum velocity, U_m, is plotted versus the radial distance in Figure 9 on logarithmic coordinates for one of the tests run on the flat plate. The slope of the line passing through the data is the average of the slopes obtained from the least squares curve fits for three test runs; the natural logarithm of the maximum velocity was taken as the dependent variable. The resulting slope was -1.04 or

$$U_m \propto R^{-1.04}$$

The error in the calibration of the probe was 5% of the calibration constant. Also, due to the turbulent nature of the flow the reliability of the velocity measurements can not be considered to be better than 10% of the value; this estimate is based on checks of data reproducibility.

The data from the tests on the hemispheres were first plotted as strictly the boundary layer thickness or maximum velocity versus the radial distance measured along the surface of the hemisphere. A least squares curve fit yielded

$$\delta \propto R^{0.78}$$

for the boundary layer thickness and

$$U_m \propto R^{-0.89}$$

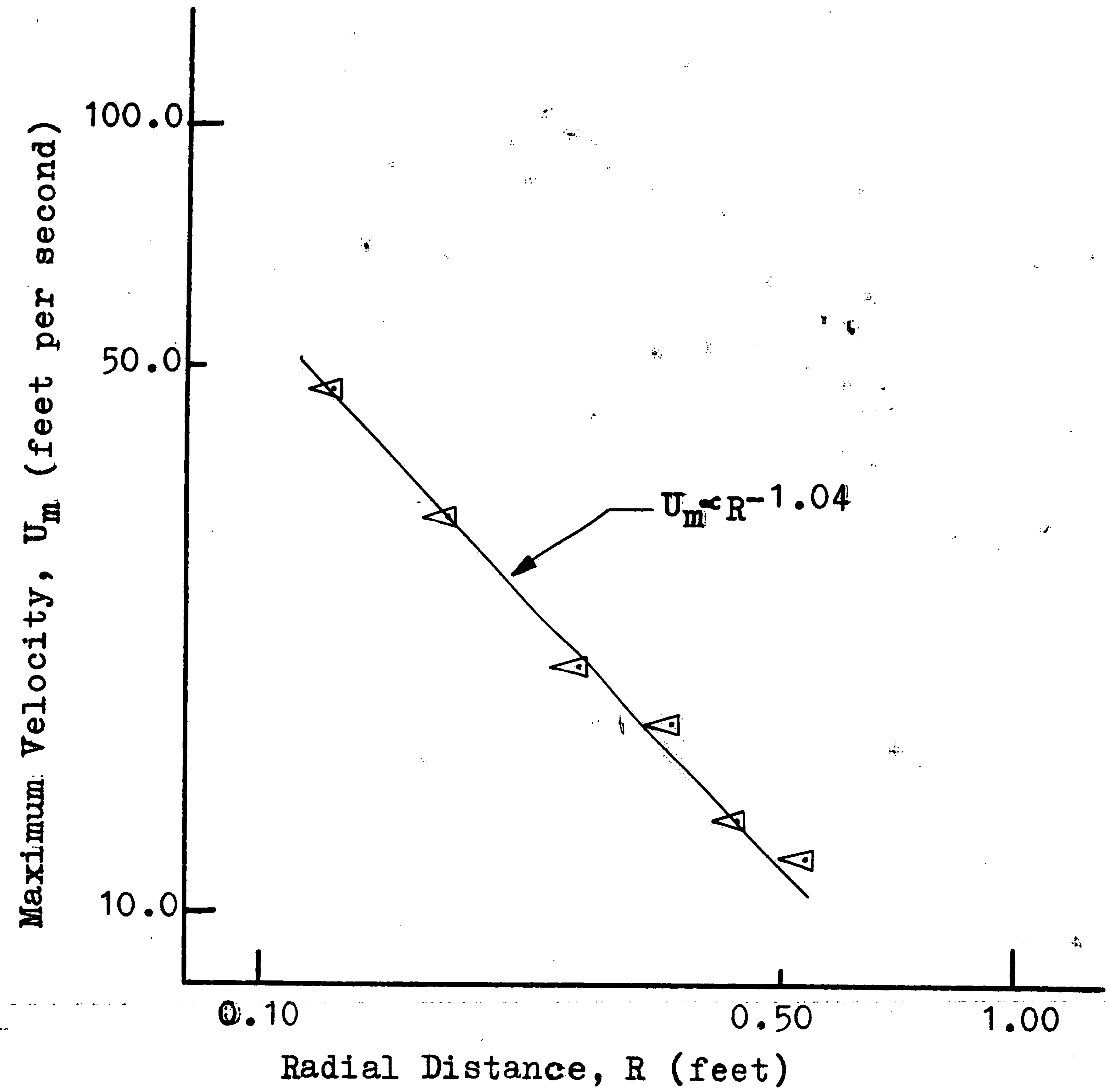


Figure 9. Decay of the Maximum Velocity on the Flat Surface

for the decay of the maximum velocity. Figure 10 is a plot of the boundary layer thickness versus the radial distance; the solid line is the curve fitted line and broken lines designate the 95% confidence band. An adjustment was then made for the surface curvature effect and the quantities $(\delta)(A)\sin(\theta)$ and U_m were plotted against $\overline{R} = A^3(2\theta - \sin(2\theta))$ where A is the radius of the hemisphere and θ is the angle measured from the center of the 1.0 inch diameter button to the tip of the probe. This adjustment was derived by Riley(4) for the case of a laminar radial wall jet on a concave surface of revolution; although there is no theoretical basis for its application to the turbulent wall jet it was thought that it might be used to correlate the data. The exponents on the adjusted distance coordinate which satisfied the proportionality with the adjusted boundary layer thickness and the maximum velocity were 0.64 and -0.31 respectively. The mean percent deviation from the fitted curve was 8.1% for the adjusted plot versus 14.2% for the unadjusted and the maximum percent deviation was 25% versus 45%. Figure 11 is a plot of the boundary layer thickness with this adjustment for curvature; one test run from each hemisphere is shown. The slope of the solid line is 0.64 and the broken lines

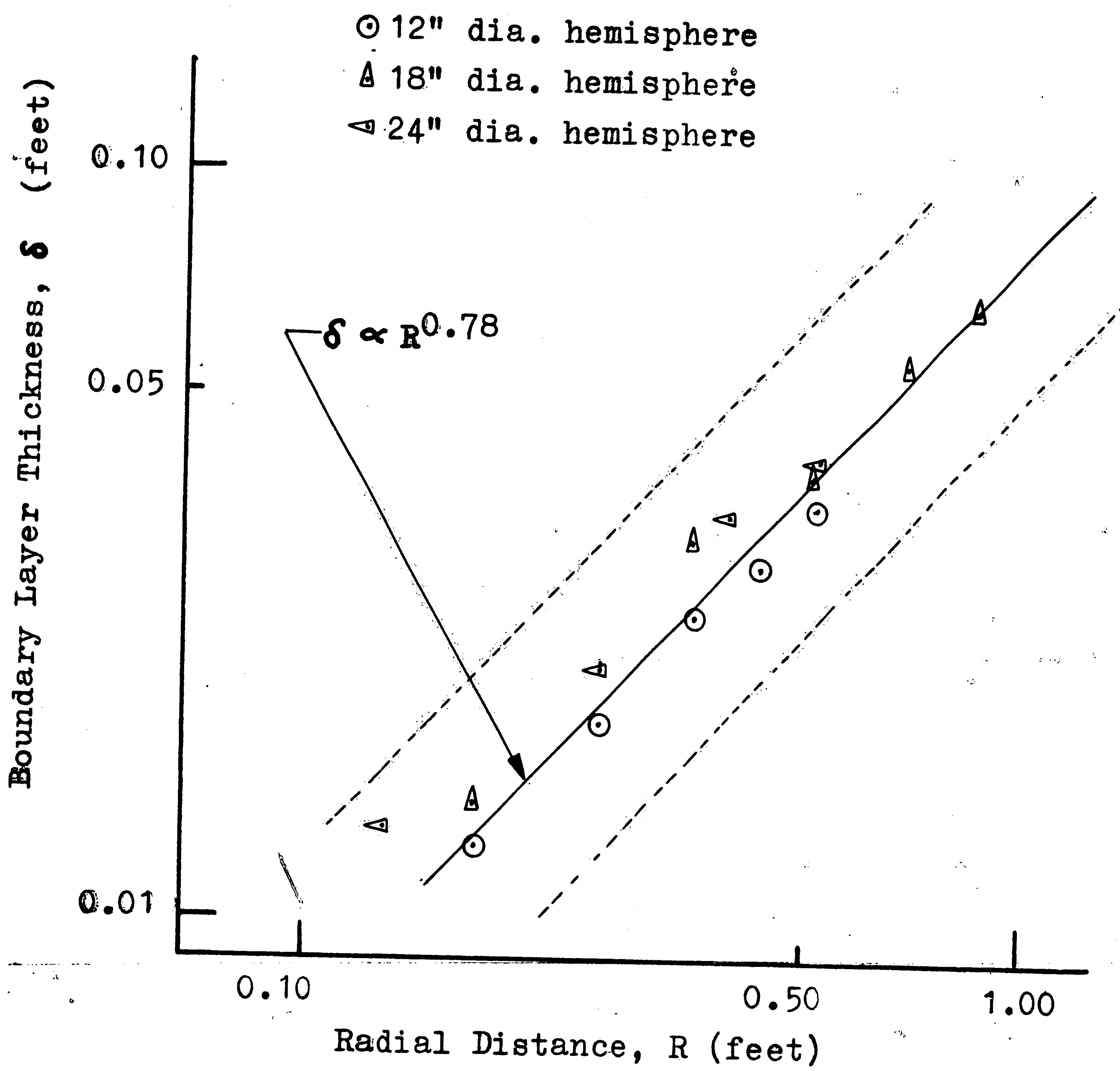


Figure 10. Boundary Layer Growth on Concave Surfaces

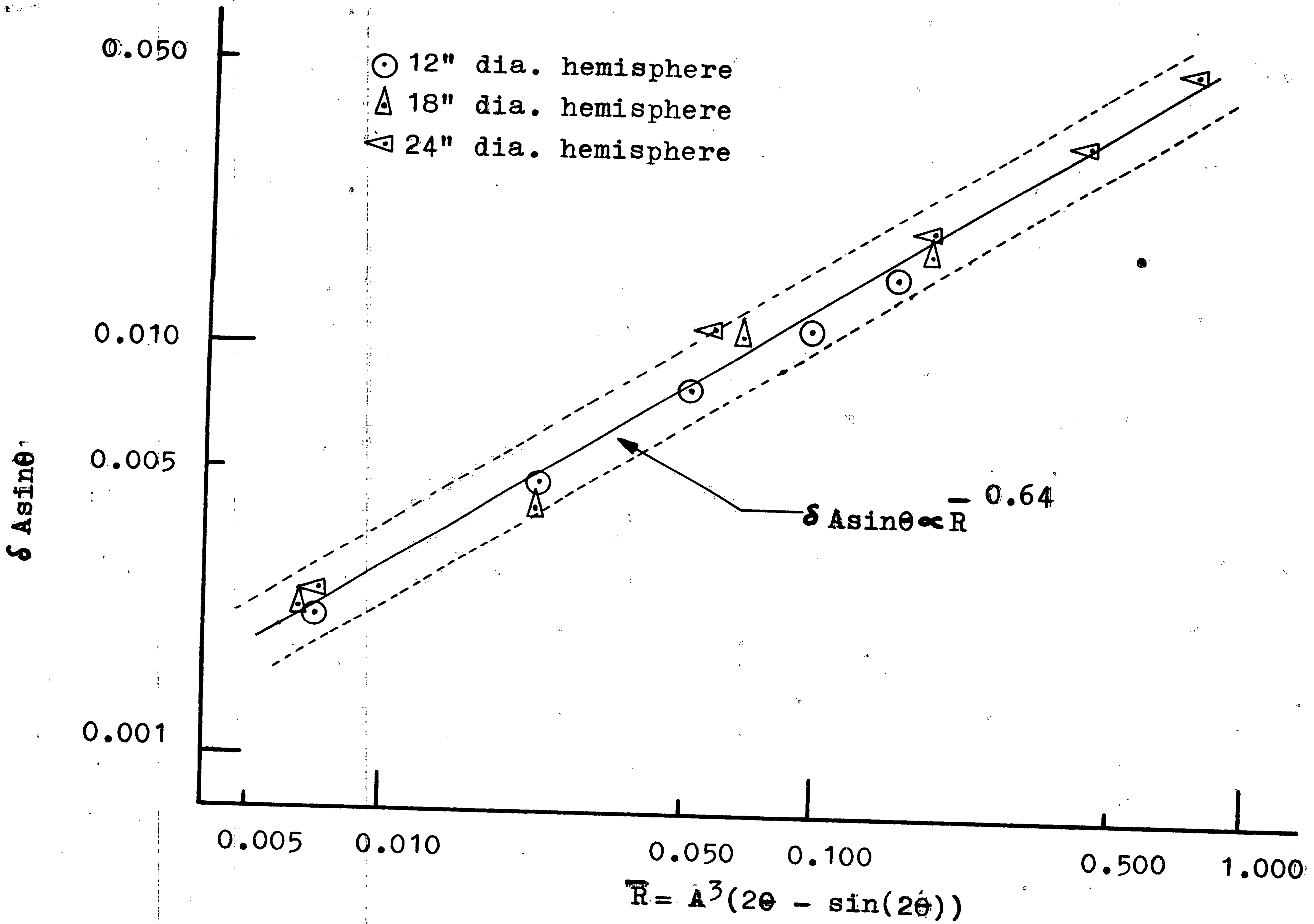


Figure 11. Boundary Layer Growth on Concave Surfaces Utilizing Riley's Curvature Adjustment

represent the 95% confidence band. Figure 12 is a plot of maximum velocity versus the adjusted distance coordinate. The slope of the lines drawn through the data, -0.31, is an average based on the data from all three hemispheres. In another attempt to adjust for the curvature effect (A)sin(θ) was used as the radial distance parameter. A plot of δ versus (A)sin(θ) is shown in Figure 13; the curve fitted line through the data has a slope of 1.04. The shape of the velocity profiles occurring on the 12 and 18 inch diameter hemispheres and the flat plate as the flow progresses in the radial direction is shown in a series of plots in Figure 15. Figure 15-A shows the velocity profiles which were matched 1.0 inch from the exit.

The wall jet velocity profiles can be plotted dimensionlessly if the distances from the surface are divided by the boundary layer thickness and the velocities are divided by the maximum velocity. Dimensionless plots for the 12, 18 and 24 inch diameter hemispheres and the flat surface appear in Figures 16, 17, 18 and 19 respectively. Each plot consists of two profiles taken at different locations and the same initial jet velocity and a third at a different initial velocity and location. In Figure 20 one profile from each hemisphere and one

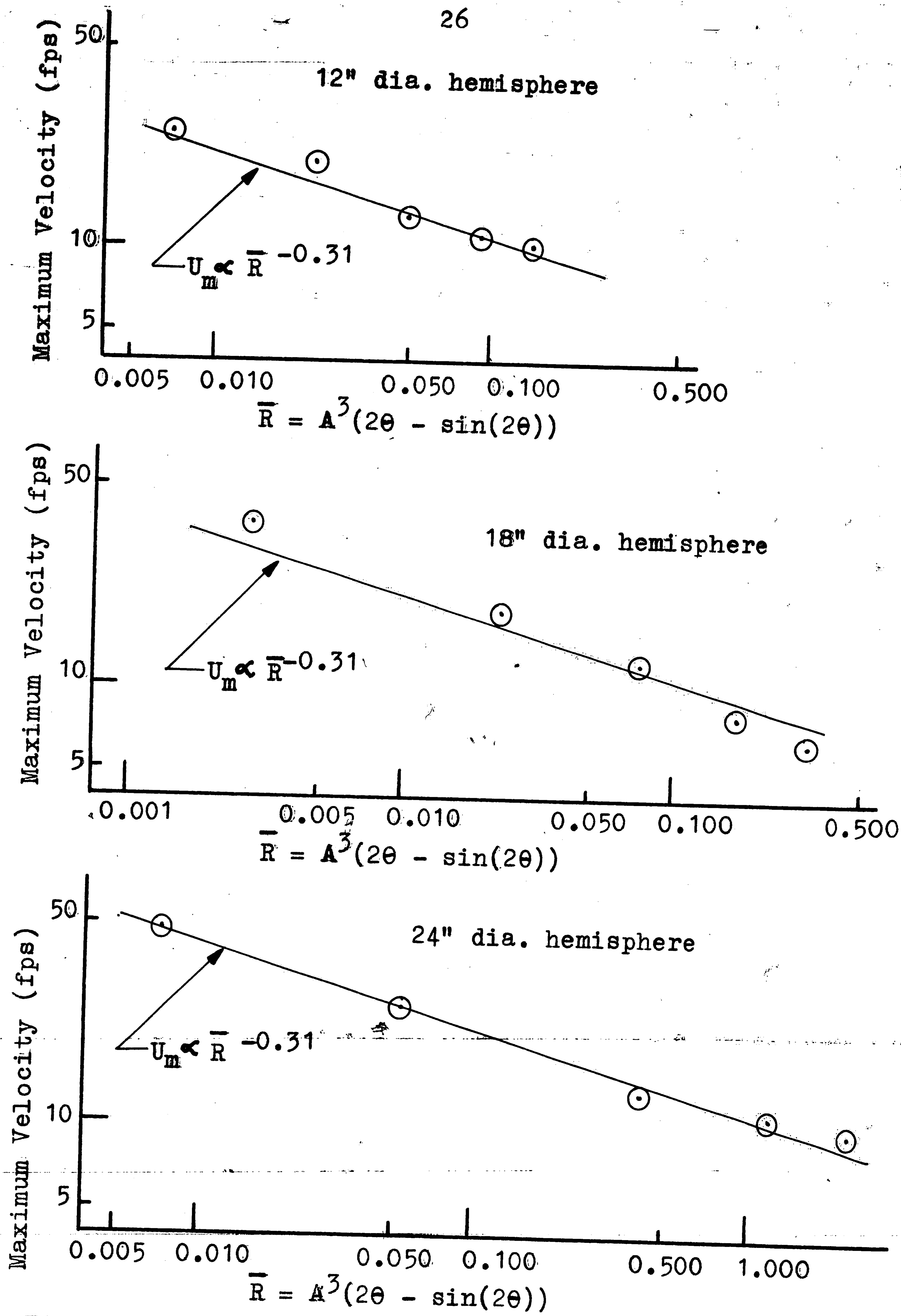


Figure 12. Decay of the Maximum Velocity on Concave Surfaces Utilizing Riley's Curvature Adjustment

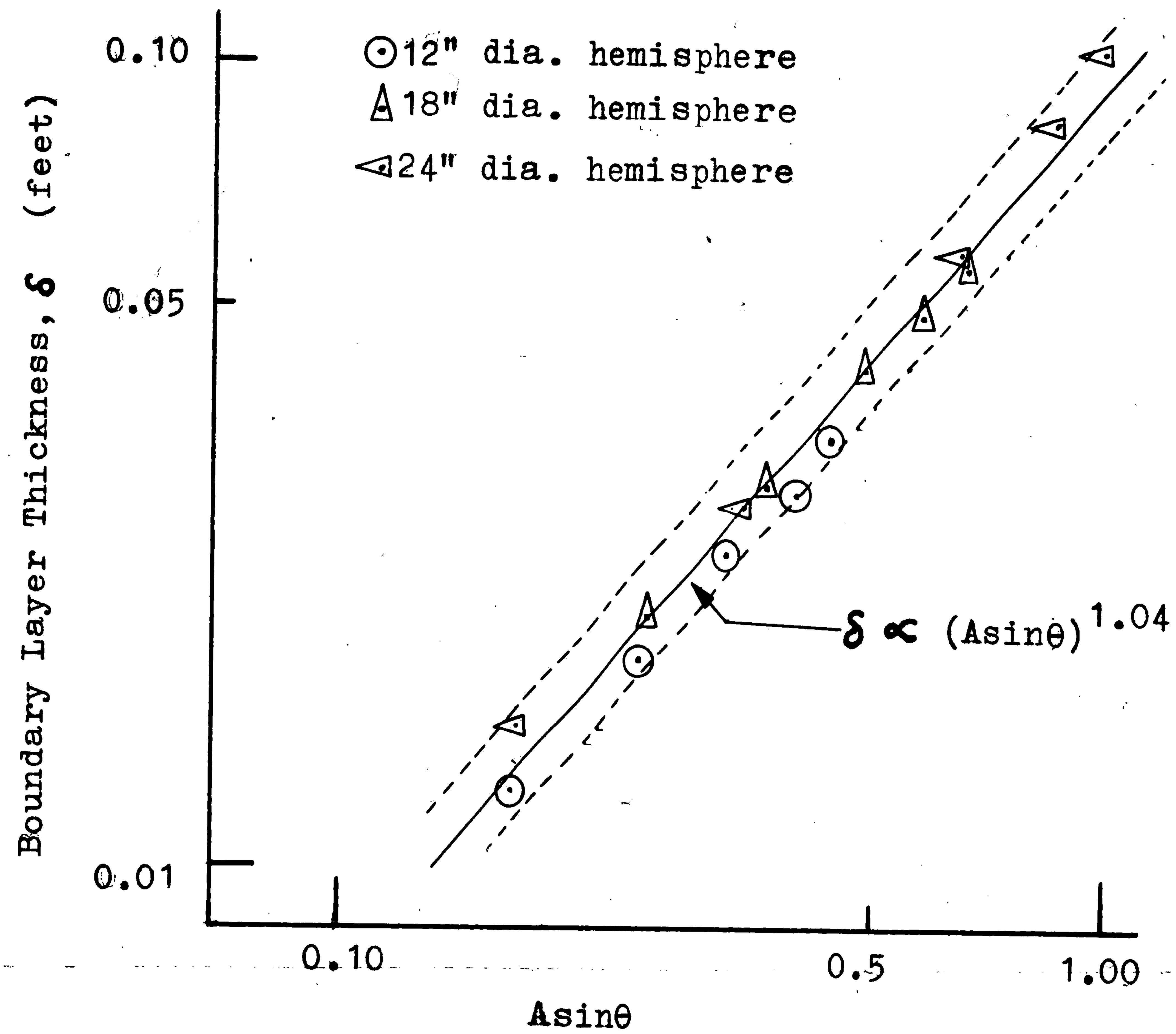


Figure 13. Boundary Layer Growth on Concave Surfaces Utilizing Asinθ as the Curvature Adjustment

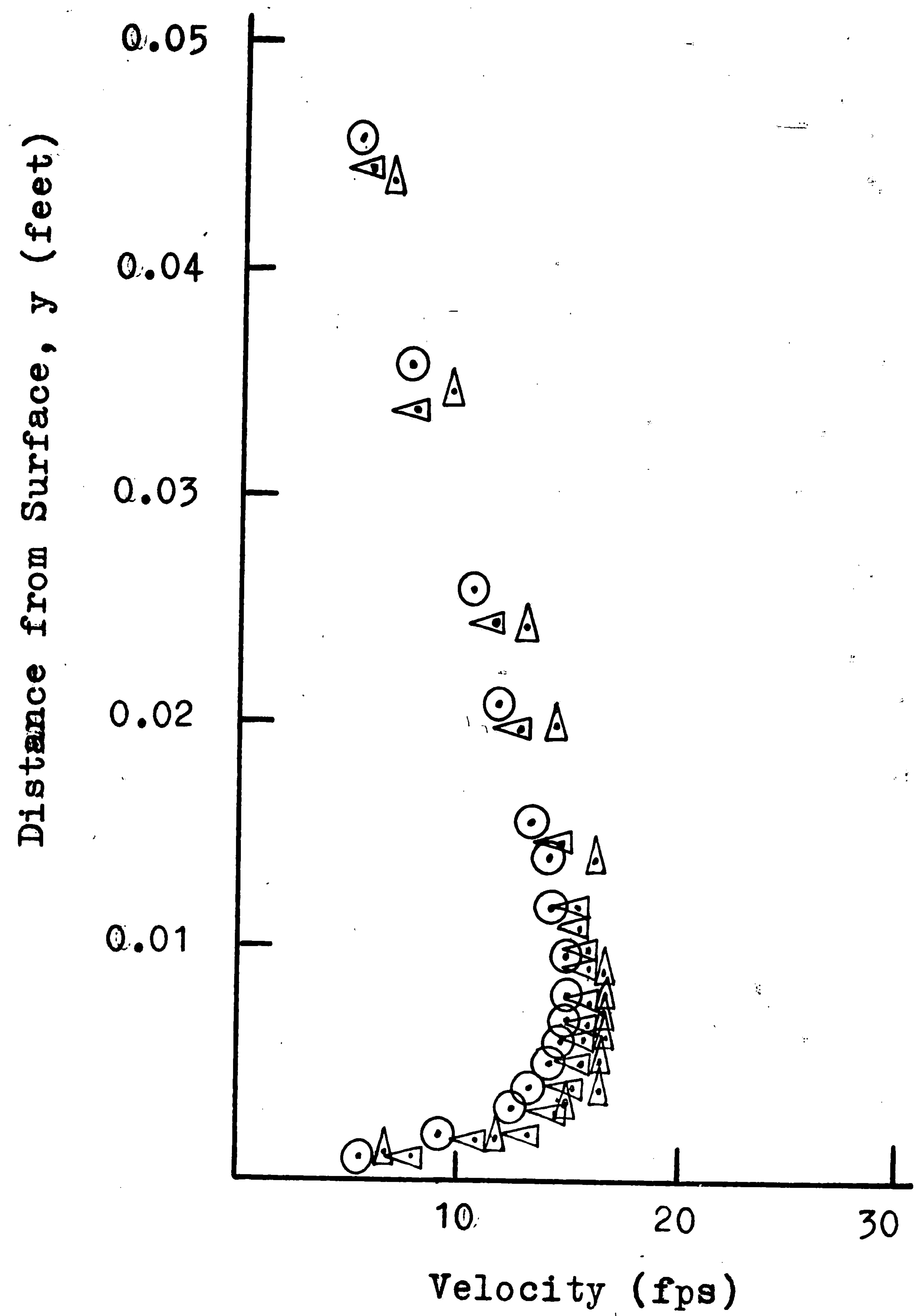
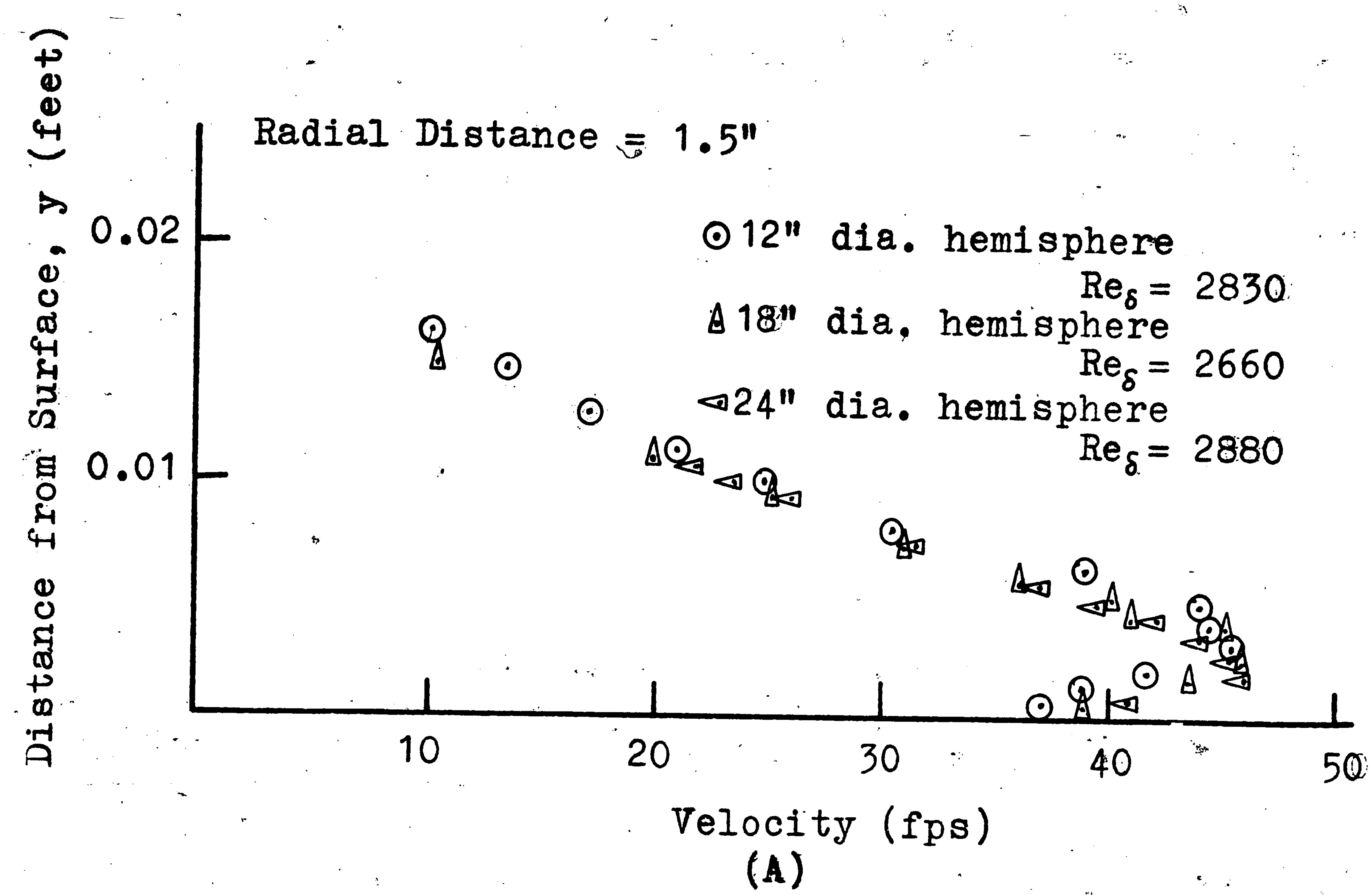


Figure 14. Symmetry Check on 18" Diameter Hemisphere



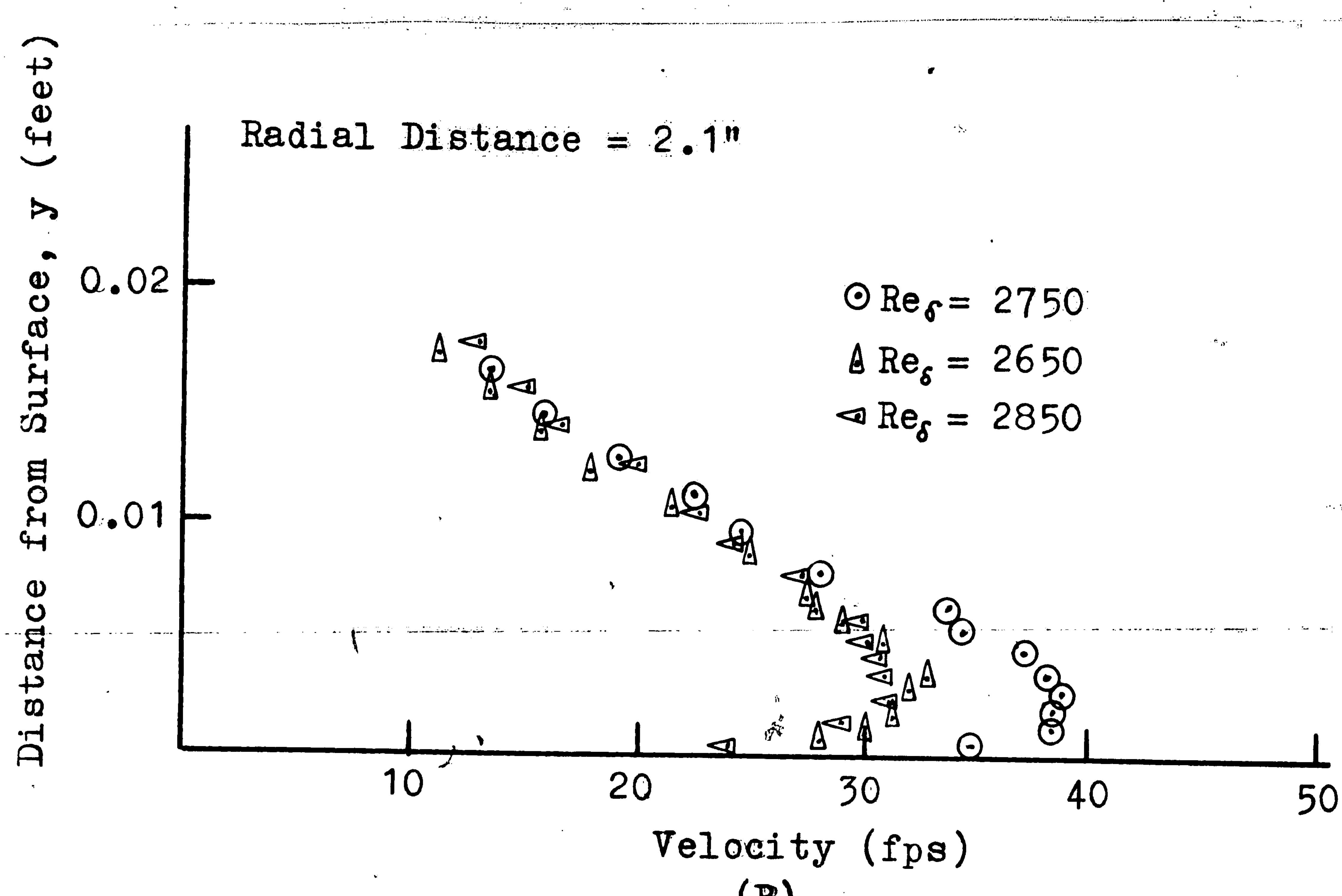
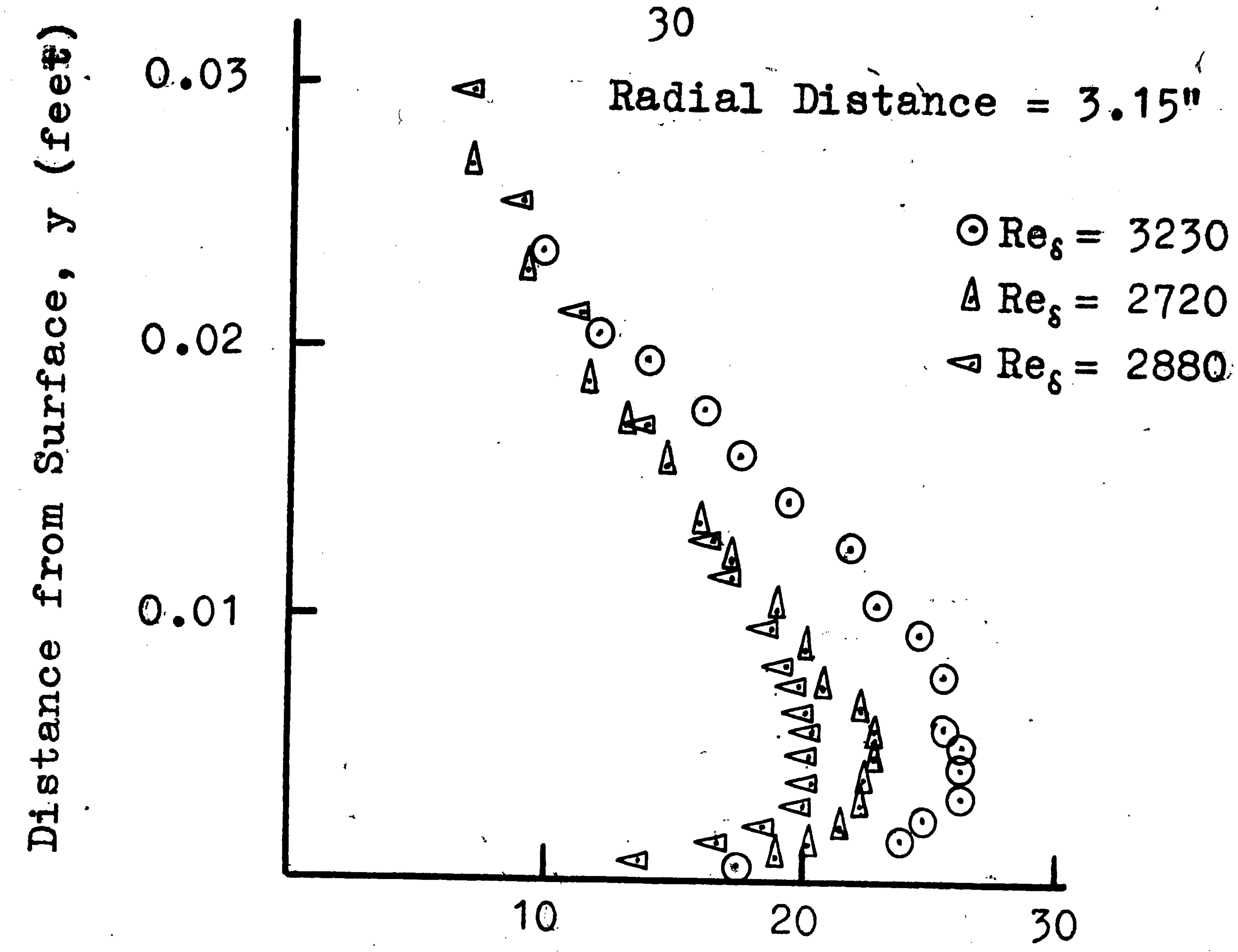


Figure 15. Comparison of Velocity Profiles as a Function of Radial Distance



(C)

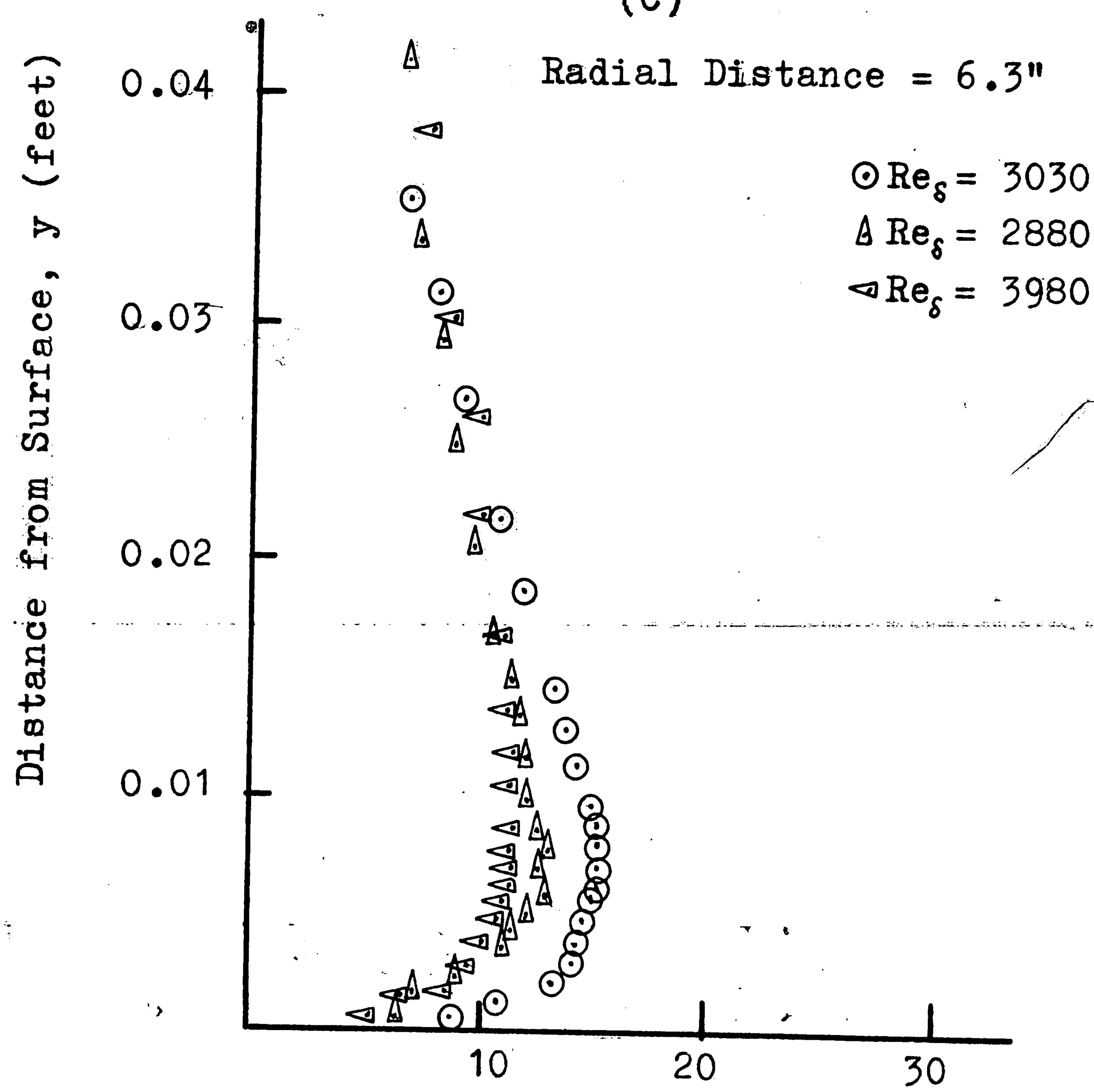


Figure 15 (cont'd)

(D)

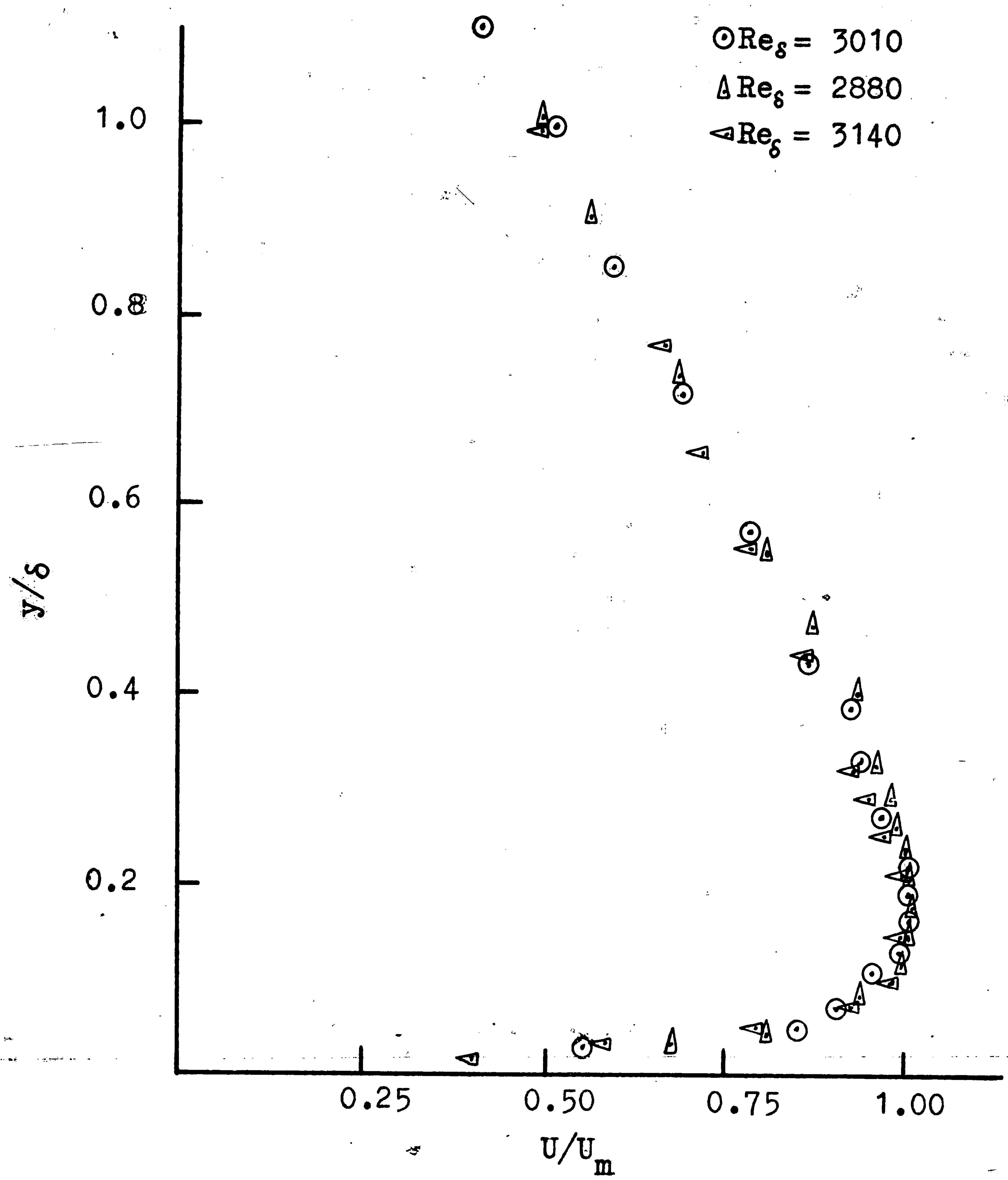


Figure 16. Dimensionless Velocity Profiles for the Flat Surface

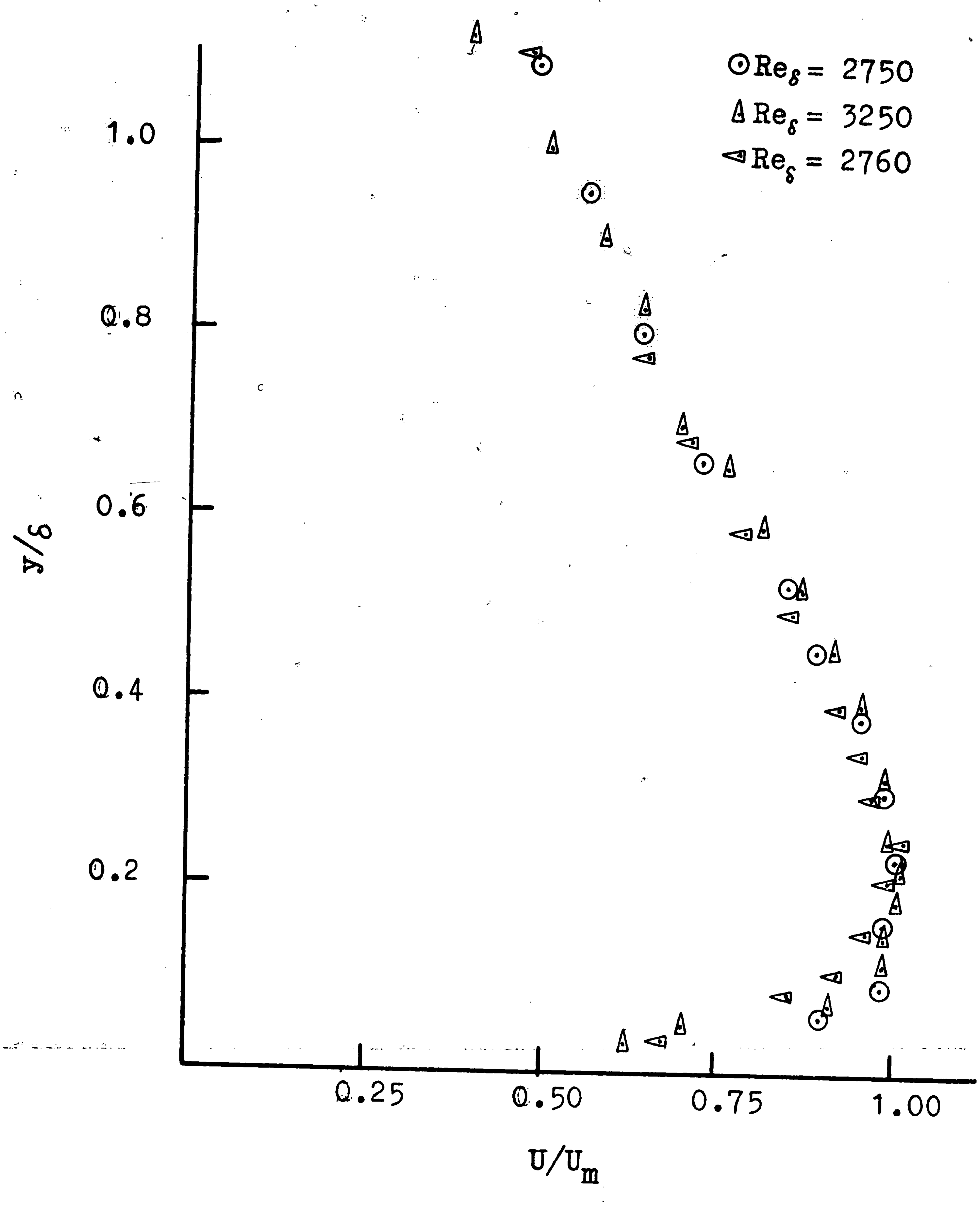


Figure 17. Dimensionless Velocity Profiles for the 12" Diameter Hemisphere

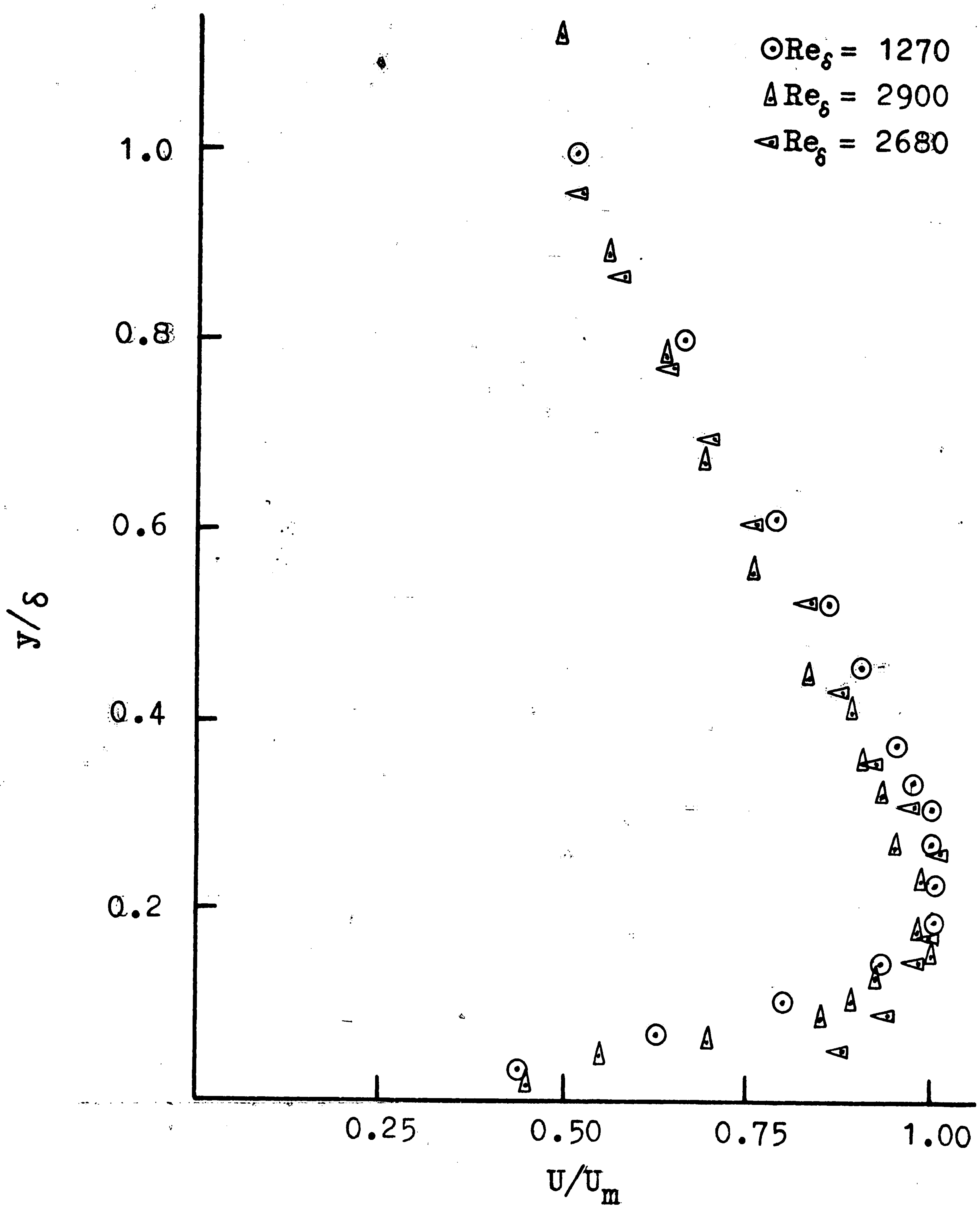


Figure 18. Dimensionless Velocity Profiles for the 18" Diameter Hemisphere

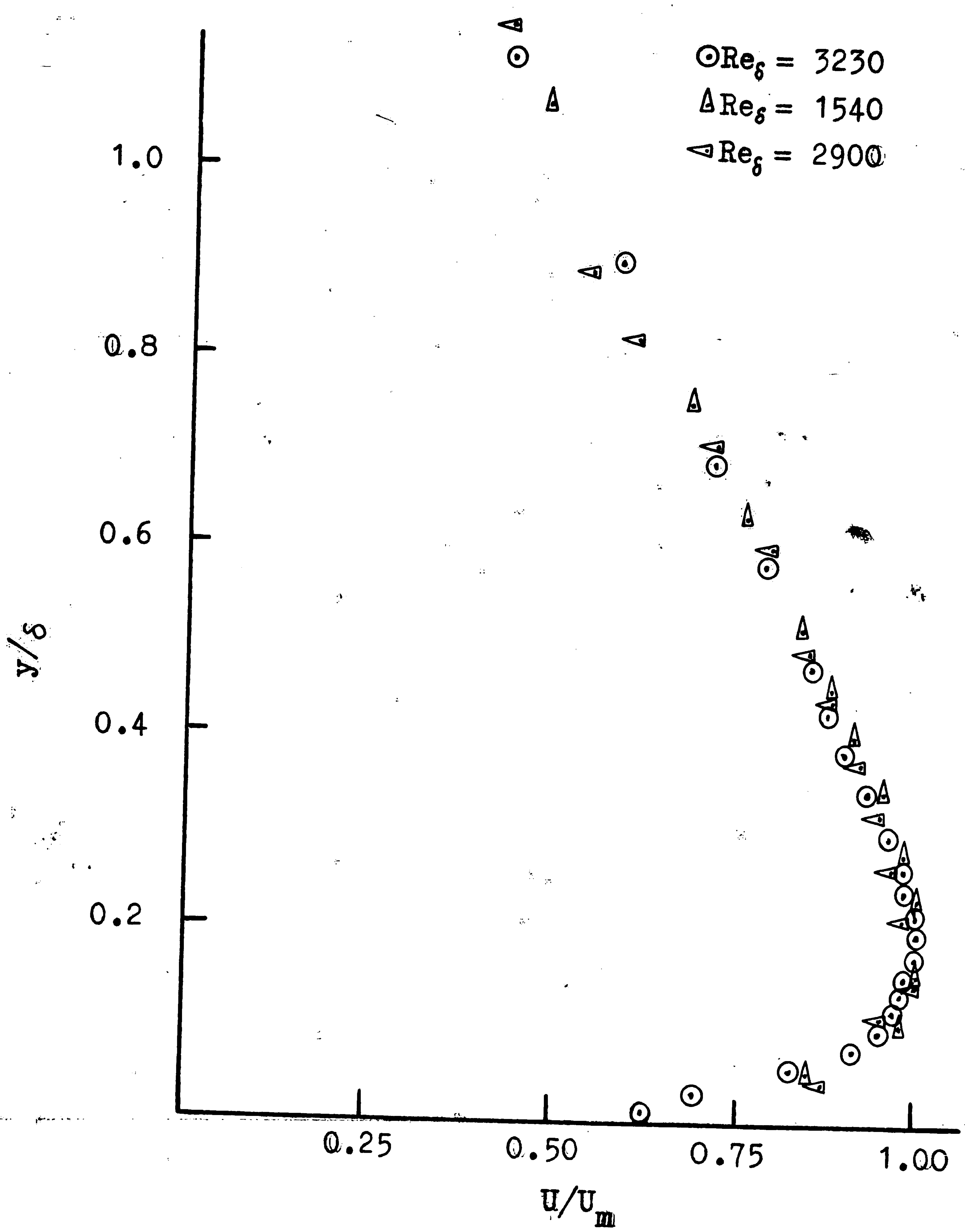


Figure 19. Dimensionless Velocity Profiles for the 24" Diameter Hemisphere

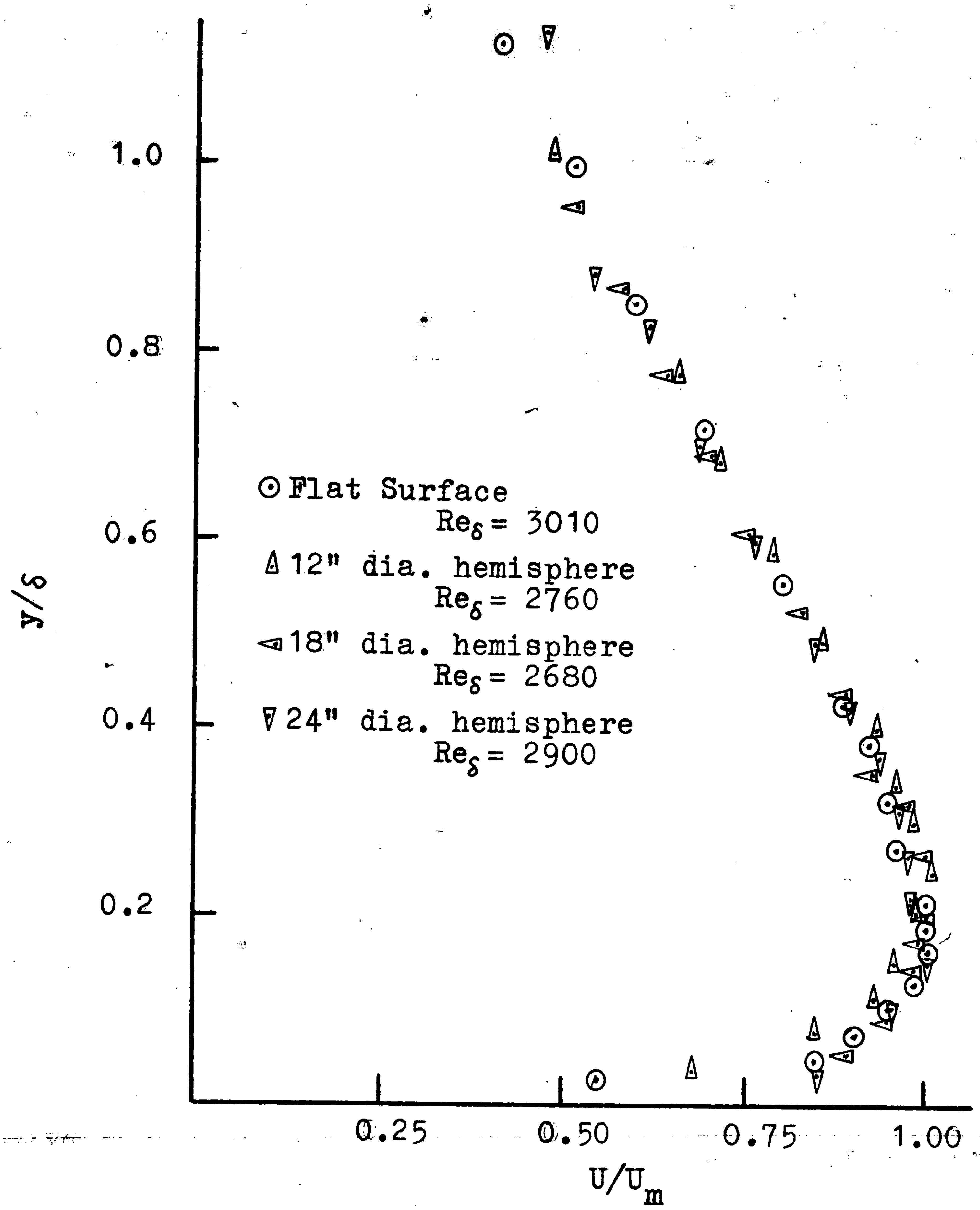


Figure 20. Comparison of the Dimensionless Velocity Profiles occurring on the Concave Surfaces and the Flat Surface

from the flat surface is plotted dimensionlessly. A comparison between Glauert's theoretical velocity profile and the one obtained experimentally for the flat surface is shown in Figure 21.

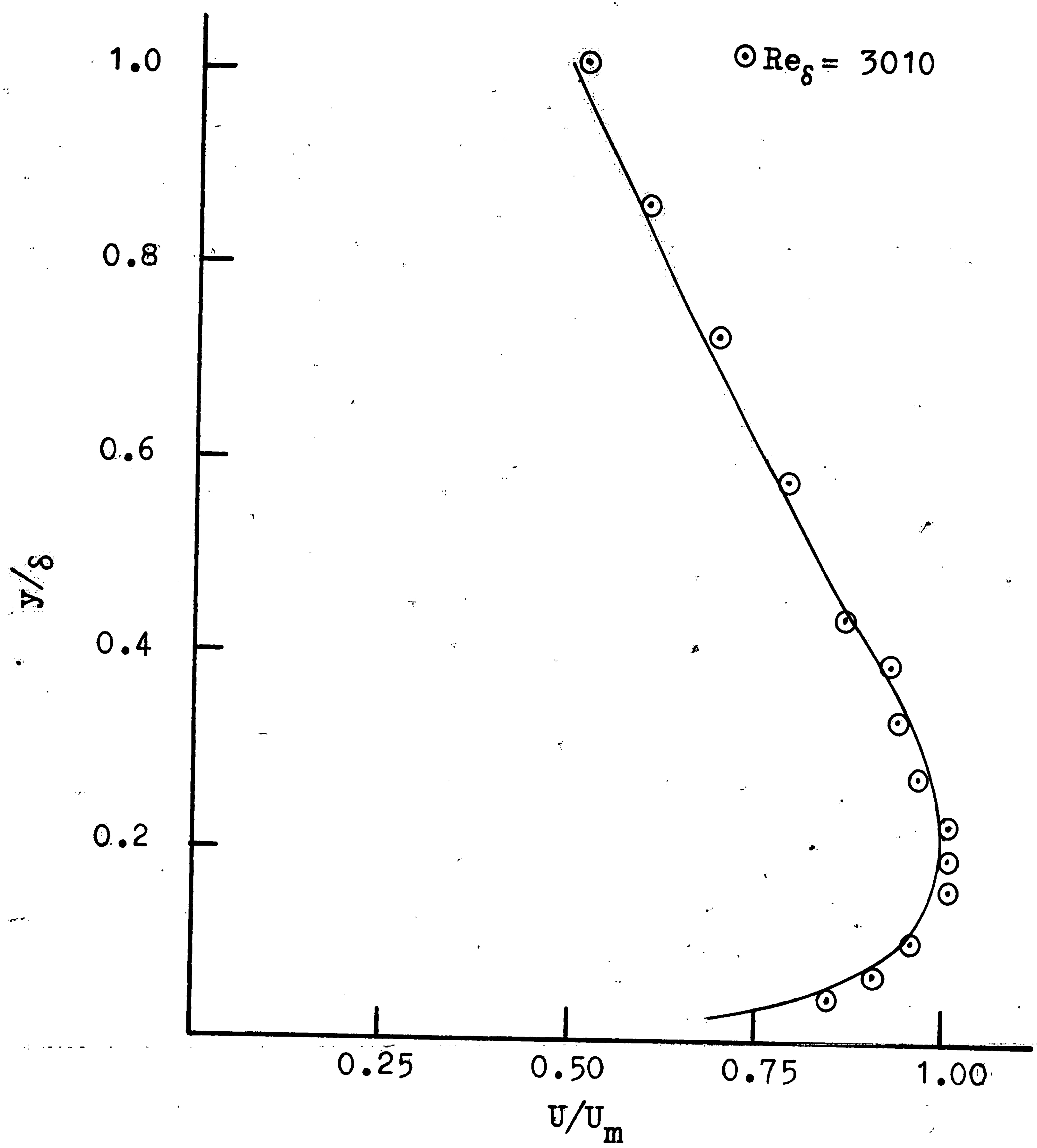


Figure 21. Comparison of Glauert's Theoretical Velocity Profile and the Results from the Flat Surface

Conclusions

Based on the results of this experimental investigation it can be concluded that the effects of curvature on a turbulent radial wall jet are to decrease the rate at which the maximum velocity decays and to decrease the rate of boundary layer growth.

When the boundary layer thickness was plotted versus the radial distance it was found that the boundary layer thickness was proportional to the radial distance to the 1.18 power for the flat surface and the 0.78 power for the hemispheres. It was felt that some adjustment should be made for the curvature effect of the hemispheres. The boundary layer thickness was plotted against Asinθ which seemed to be a more obvious adjustment and then an adjustment derived by Riley for laminar radial wall jets was tried. Since the Asinθ adjustment does not differ greatly from the actual radial distance until θ becomes large and the curvature effect would not be expected to appear until the flow progressed a significant distance along the curvature, this would seem to be a logical adjustment. However, it is felt that the data plotted with Riley's curvature adjustment lended itself to a better curve fit.

The rate at which the maximum velocity decays is subject to a curvature effect as witnessed in Figure 15. When the proportionality of the maximum velocity to the radial distance was considered the resulting exponents on the radial distance were -1.04 for the flat surface and -0.89 for the hemispheres. The maximum velocity was also plotted against Riley's adjusted radial distance parameter.

The effect of curvature can be seen to decrease with the increase of the radius of curvature. In Figure 15 it can be observed from the series of velocity profiles that the effect is most pronounced on the 12 inch diameter hemisphere and the 18 inch diameter hemisphere displays less of the effect and attenuates to the flat surface velocity profiles for the smaller and larger radial distances. For radii of curvature larger than 9 inches the effect of the curvature appears to be negligible.

The surface curvature does not effect the dimensionless plots of the velocity profiles. The growth at the boundary layer and the decay of the maximum velocity are so coupled that when the velocity profiles are plotted dimensionlessly the curvature effect is cancelled.

The results of the analysis done by Glauert for the turbulent radial wall jet on a flat surface when the surrounding medium was stagnant predict the boundary layer thickness to be proportional to the radial distance to the 1.02 power and the maximum velocity to be proportional to the radial distance to the -1.14 power when $\alpha = 1.3$, where α is related to the Reynolds number based on the boundary layer thickness and maximum velocity. The experimental investigation of Bakke found the exponents on the radial distance which satisfied the proportionality with the boundary layer thickness and maximum velocity to be 0.94 and -1.12 respectively. Poreh, Tsuei and Cermak found the exponents to be 0.9 and -1.1. The agreement between the results of previous investigations and Glauert's prediction is not much better than it is for this investigation. The dimensionless velocity profiles obtained previously and the ones obtained in this investigation agree with Glauert's theoretical velocity profiles as shown in Figure 21.

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Vita

The author was born in La Plata, Maryland, on September 26, 1945, the son of Mr. and Mrs. Artie L. Pace. He attended Lehigh University, and was graduated in June 1967 with a Bachelor of Science degree in Mechanical Engineering.

Mr. Pace was a research assistant on a project funded by the National Science Foundation from Sept. 1967 to July 1968. He is at present continuing his graduate studies in mechanical engineering at Lehigh University.